FAME TIM 8/15-16/01
ADCS

- **Paul DeLaHunt (202-767-0699 or pdelahunt@space.nrl.navy.mil)**
- **Tae Lim (202-404-1015 or tlim@space.nrl.navy.mil)**
- **Glenn Creamer (202-404-3530 or gcreamer@space.nrl.navy.mil)**
- **Bob McClelland (202-767-0698 or mcclella@ccf.nrl.navy.mil)**
- **Steve Gates (202-404-2701 or sgates@space.nrl.navy.mil)**

United States Naval Observatory

FAME ACS Design Drivers

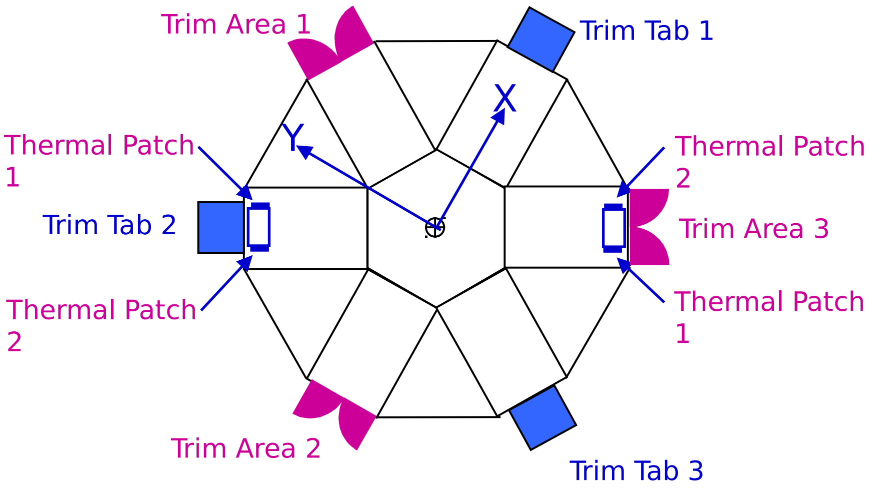
In-Scan Stability	Cross-Scan Stability	ACS/Bus Design Impact	Remarks
Spin period: 40 min +/- 4 min		Thruster sizing	
Spin rate variation: +/- 0.05 as/s over 300 sec		Inertia property	Gravity gradient torque
		Residual magnetic dipole moment	Magnetic torque
		Area tabs	CM-CP offset control, metal diaphragm propellant tank
		EMT system	
		Stringent optical property knowledge and control	CP control
		Stringent surface flatness control	CP control
	Precession period: 20 +/- 2 days Sun angle: 35 +/- 5 deg	Inertia property	Gravity gradient torque
		Residual magnetic dipole moment	Magnetic torque
		Trim tabs	Optical property variation (BOL-EOL) Mass property variation (fuel depletion)
	Nutation damping	EMT system	Handshake between thrusters and solar precession
	Spin axis alignment: < 30	Trim masses	On-orbit spin balancing

Solar Precession Control for the Redesigned FAME

Technical Interchange Meeting
August 15-16, 2001
NRL

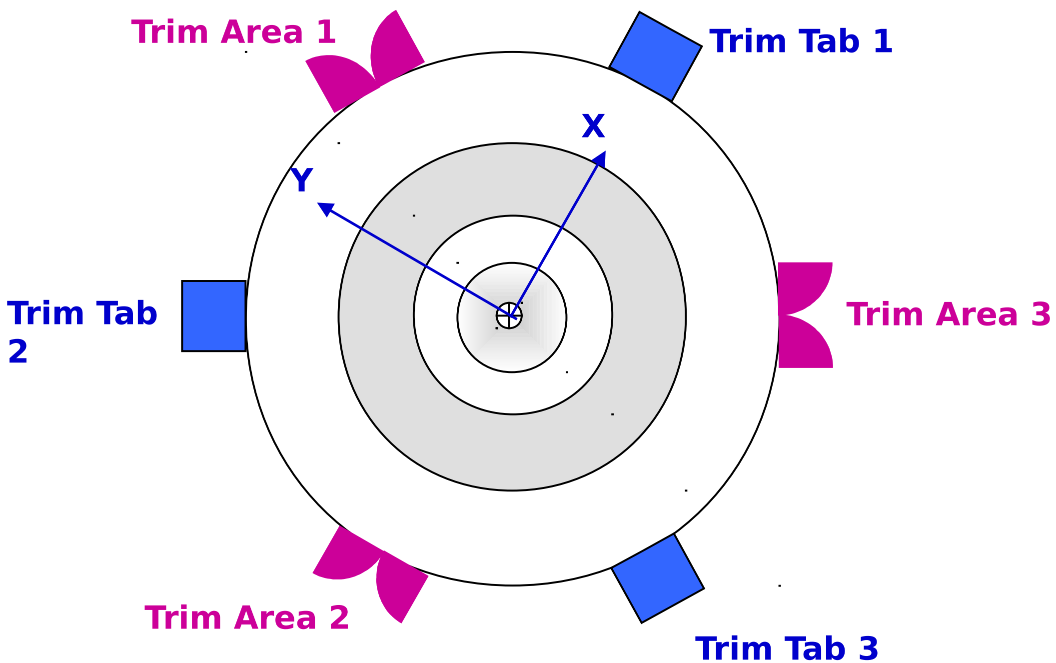
6/26-27/01 TIM Baseline

- **Swept-back sun shield for coarse solar radiation torque adjustment prior to launch**
- **Three trim tabs for solar radiation torque bias adjustment through uniform deflection**
- **Three trim areas for CP to CM balancing**
- **Trim masses for principal axis misalignment control**
- **Acquisition of instrument pointing mode with thrusters**
- **Two sets of thermal patches for fine spin axis bias torque balancing**
- **Z-axis electromagnetic torque rod for active nutation damping, precession rate control, & sun angle control**
- **X- & Y-axis electromagnetic torque rods for active spin rate control**



August 01 TIM Baseline

- Fixed sun shield/solar panel with zero sweep angle.
- Three trim tabs for solar radiation torque bias adjustment through uniform deflection
- Three trim areas for CP to CM balancing
- Trim masses for principal axis misalignment control
- Acquisition of instrument pointing mode with thrusters
- Z-axis electromagnetic torque rod for active nutation damping, precession rate control, & sun angle control
- X- & Y-axis electromagnetic torque rods for active spin rate control



Updated Mass Property Requirements (7/17/01)

- **Prior to On-Orbit Trimming**

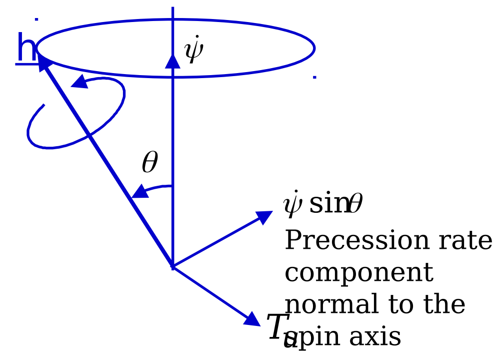
Items	Current	Updated	Remarks
Izz (spin axis, kg-m^2)	800 +/- 10%	230 +/- 10%	Redesign, fixed solar panels
Ixx	0.89 Izz ≤ Ixx ≤ 0.91 Izz	0.89 Izz ≤ Ixx ≤ 0.91 Izz	
Iyy	0.89 Izz ≤ Ixx ≤ 0.91 Izz	0.89 Izz ≤ Ixx ≤ 0.91 Izz	
|Ixx-Iyy|	≤ 0.02 Izz (TBR)	≤ 0.02 Izz (TBR)	
|Ixy|	≤ 0.025 Izz (TBR)	≤ 0.025 Izz (TBR)	
|Ixz|	≤ 5.7e-4 Izz (TBR)	≤ 5.7e-4 Izz (TBR)	0.5 deg spin axis misalignment
|Iyz|	≤ 5.7e-4 Izz (TBR)	≤ 5.7e-4 Izz (TBR)	
|XCM|	≤ 10 mm (TBR)	≤ 10 mm (TBR)	No trim mass control for radial CM
|YCM|	≤ 10 mm (TBR)	≤ 10 mm (TBR)	
ZCM	Range: 0.65 +/- 0.05 m (from th	Range: 0.05m (BOL) 0.1m (EOL)	Redesign
	top of the electronics deck)	(from the top of the solar panel	
	Knowledge: TBD	substrate) Knowledge: TBD	
|XCP|	≤ 10 mm (TBR)	≤ 10 mm (TBR)	
|YCP|	≤ 10 mm (TBR)	≤ 10 mm (TBR)	

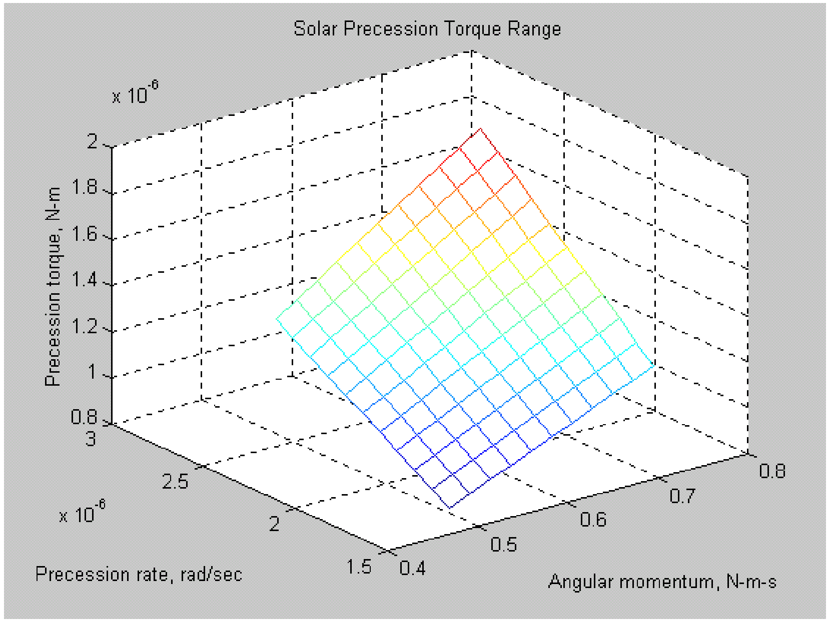
Precession Torque Range

- **Spin axis inertia (kg-m^2): 210 $\leq$ I_s $\leq$ 250**
- **Spin period (min): 40 $\pm$ 4**
- **Angular momentum range (N-m-s): 0.50 $\leq$ h_s $\leq$ 0.73**

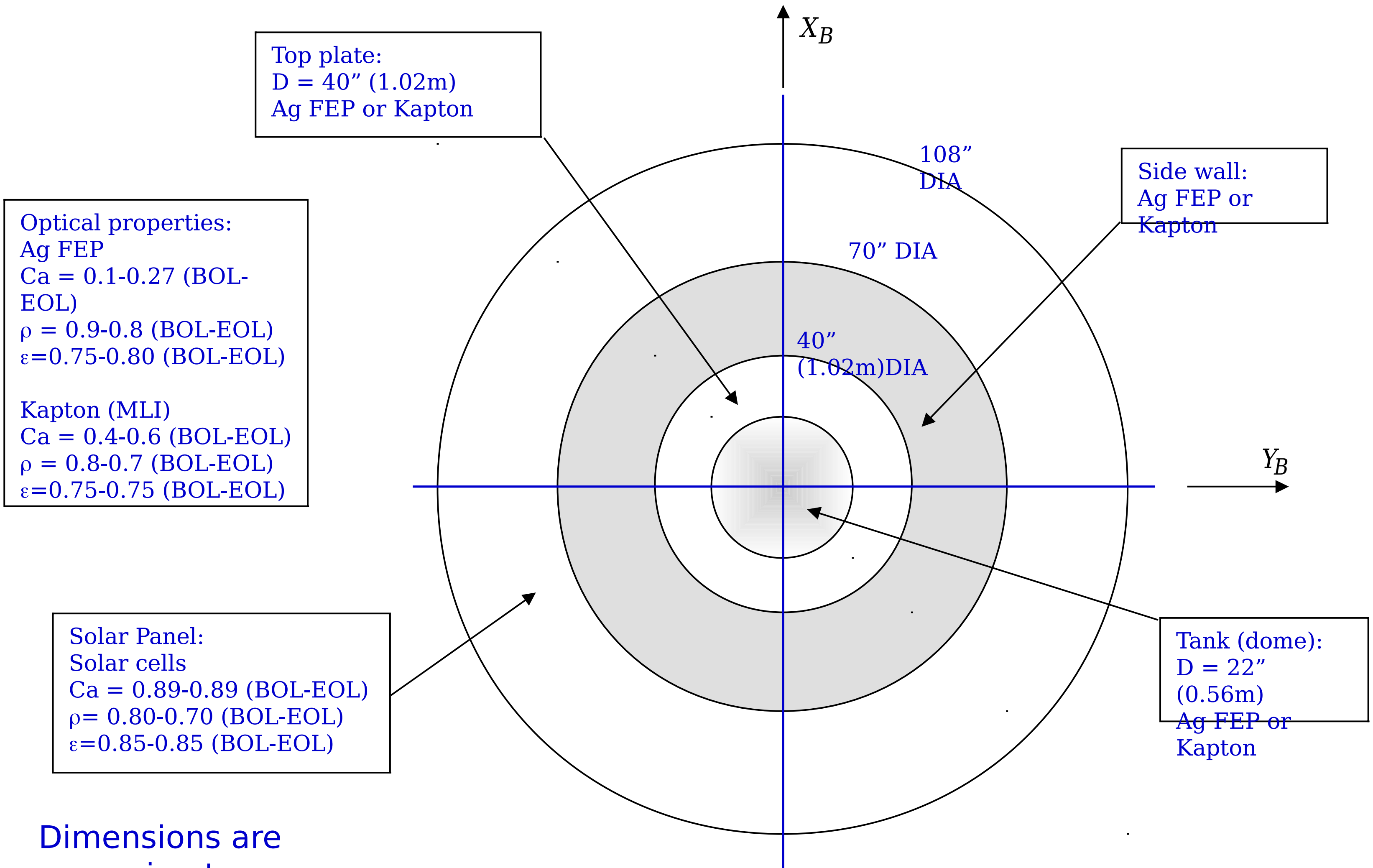
- **Precession period (days): 20 $\pm$ 2**
- **Sun angle (deg): 35 $\pm$ 5**
- **Precession rate range (μrad/sec): 1.65 $\leq$ $\dot{\psi}_n$ $\leq$ 2.60**

- **Nominal precession torque (μN-m): 1.26**
- **Precession torque range (μN-m):**
  0.83 $\leq$ T_u $\leq$ 1.89 or T_u = 1.36 $\pm$ 0.53





Sun Shield Geometry / Optical Properties



Dimensions are approximate.
Seen from the sun side.

Solar Precession Control Requirements

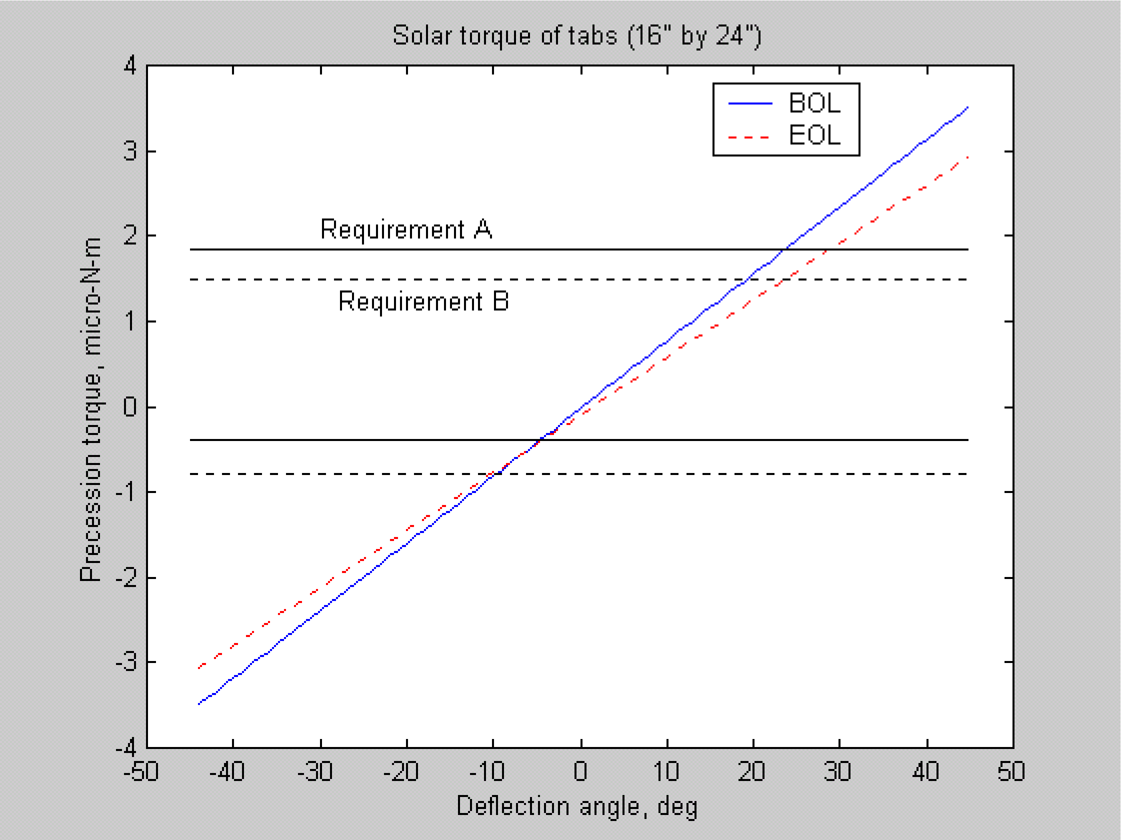
- **Accommodate:**
  - **BOL and EOL optical properties**
  - **Axial CM offset (BOL to EOL)**
  - **Thermal radiation torque**
  - **Spin rate variation**
  - **Precession rate variation**
  - **Sun angle variation**
  - **Spin inertia variation**
- **Trim torque range needed for solar precession:**
  - **1.83 to -0.38 with Ag FEP coating**
  - **1.50 to -0.78 with MLI (Kapton) coating**

Surface coating	Ag FEP	Ag FEP	MLI	MLI	
Torque (Tu, 1e-6 N-m)	BOL	EOL	BOL	EOL	Remarks
Axial CM distance from solar panel	3 inch	6 inch	3 inch	6 inch	Due to tank depletion
Solar panel	0.51	1.03	0.51	1.03	
Side wall	-0.85	-0.49	-0.75	-0.31	
Top panel	0.12	0.31	0.33	0.53	
Tank	0.29	0.36	0.3	0.36	
Total solar radiation torque	0.07	1.21	0.39	1.61	
Solar panel	0	0	0	0	
Side wall	-0.02	-0.04	0	-0.1	
Top panel	0	0	0	0	
Tank	0.01	0.02	0.04	0.06	
Total thermal radiation torque	-0.01	-0.02	0.04	-0.04	
Solar panel	0.51	1.03	0.51	1.03	
Side wall	-0.87	-0.53	-0.75	-0.41	
Top panel	0.12	0.31	0.33	0.53	
Tank	0.3	0.38	0.34	0.42	
Total solar and thermal radiation torque	0.06	1.19	0.43	1.57	
Precession torque needed	**1.36**	**1.36**	**1.36**	**1.36**	
Trim torque needed:					
Solar radiation only case	1.29	0.15	0.97	-0.25	
Solar + thermal radiation case	1.3	0.17	0.93	-0.21	
Trim torque needed including inertia, spin and precession rates, and sun angle variation requirements (+/- 0.53)					
Solar radiation only case (min)	0.76	-0.38	0.44	-0.78	
Solar radiation only case (max)	1.82	0.68	1.50	0.28	
Solar + thermal radiation case (min)	0.77	-0.36	0.40	-0.74	
Solar + thermal radiation case (max)	1.83	0.70	1.46	0.32	

Trim Tab Sizing for Precession Control

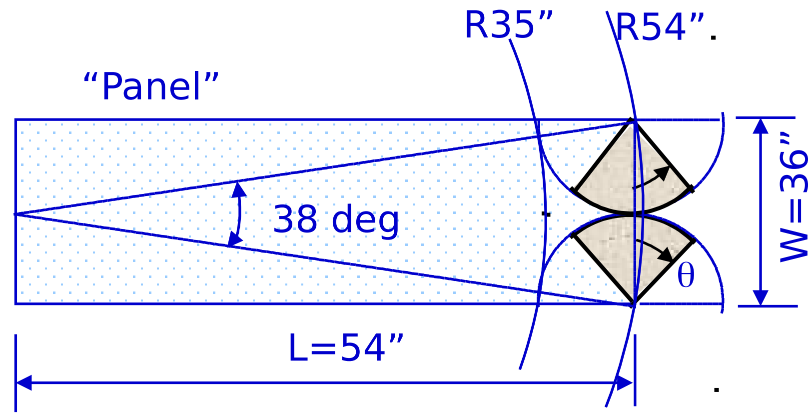
- **Control torque requirement (T_u, 10^{-6} N-m):**
  - **Requirement A: 1.83 to -0.38 with Ag FEP coating**
  - **Requirement B: 1.50 to -0.78 with MLI (Kapton) coating**

- **Trim tab specification:**
  - **3 total, 120 deg apart**
  - **Ag FEP coating**
  - **Backside blanketed**
  - **16” by 24” (384 in^2 or 0.25 m^2) rectangle, longer dimension attached to the panel**



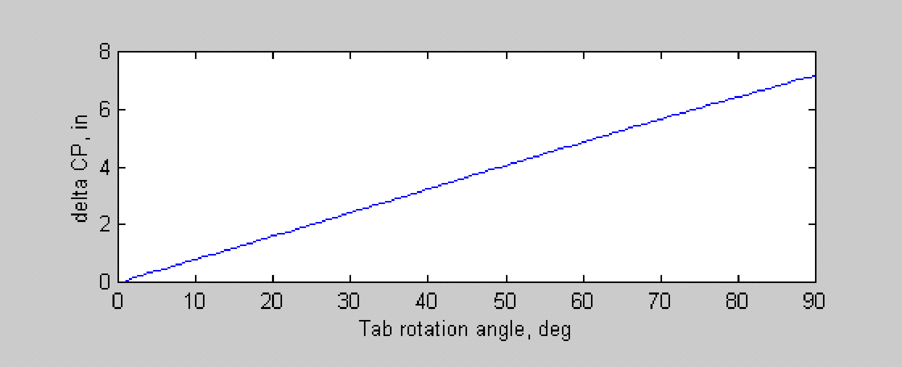
Trim Area Sizing for CP-CM Offset Control

- **Trim Area Geometry (a quarter circle of 18” radius, 254 in^2)**



Function	Rotating Tabs (a pair as a unit)
Area adjustment	$\frac{W^2\theta}{4}$
Corresponding CP change of the tab	$\frac{W(1-\cos\theta)}{3\theta}$
Corresponding CP change of the panel	$\frac{\frac{WL^2}{2}+\frac{W^2\theta}{4}\left[L+\frac{W(1-\cos\theta)}{3\theta}\right]}{WL+\frac{W^2\theta}{4}}-\frac{L}{2}$

- **Panel CP Change**



- **Maximum sun shield CP change is expected to be about 1/10 of the maximum panel CP change, that is 0.7 inch or 18 mm.**
- **Coordination of three area tabs produces about 1 inch or 25 mm sun shield CP offset meeting the 20 mm requirements.**
- **Area tab size can be increased, if needed.**

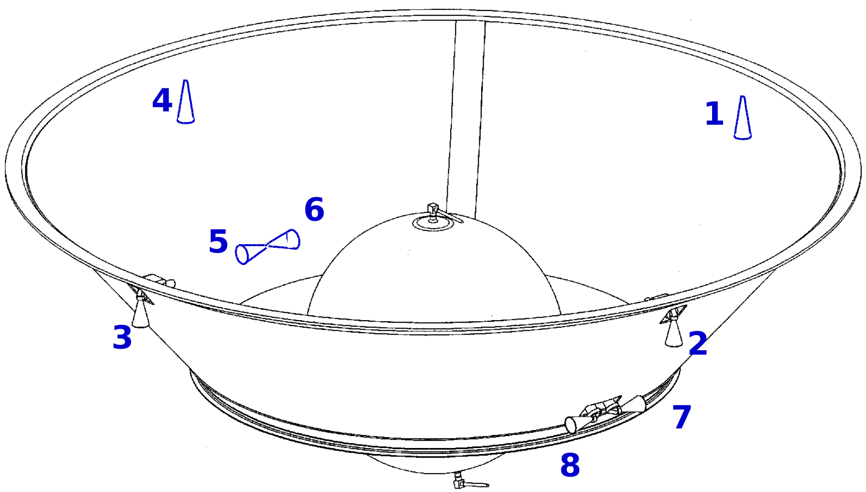
Thruster Design Updates

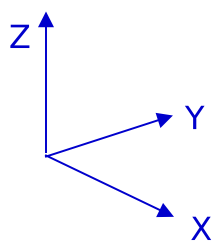
Technical Interchange Meeting
August 15-16, 2001
NRL

Thruster Configuration Update

- New FAME configuration affords reduced thruster set
  - 8 thrusters instead of 12 (because no longer lose use of some thrusters as occurred with deployable sun shield)
- New FAME configuration provides more favorable mass properties for GTO phase
  - Reduced ACS propellant budget: was 34 kg Hydrazine, now 20 kg
    - Reduced prop for spin-up/down, active nutation control
  - Reduced number of 5lbf jets from four to two-- more than adequate for ANC

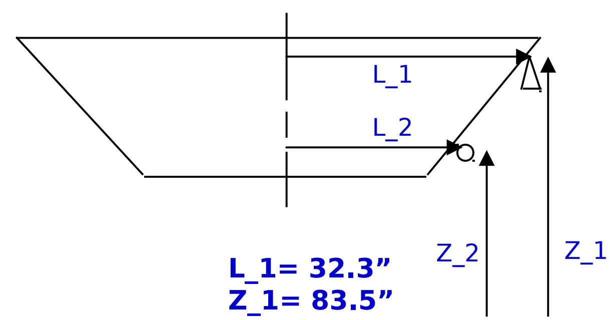
Thruster Configuration





Thruster sizing
1,3: 5 lbf
2,4,5-8: 0.22 lbf

ID	Thrust unit vecto		
	x	y	z
1	0	0	1
2	0	0	1
3	0	0	1
4	0	0	1
5	0	1	0
6	0	-1	0
7	0	-1	0
8	0	1	0



L_1= 32.3”
Z_1= 83.5”
L_2= 23.0”
Z_2= 71.8”

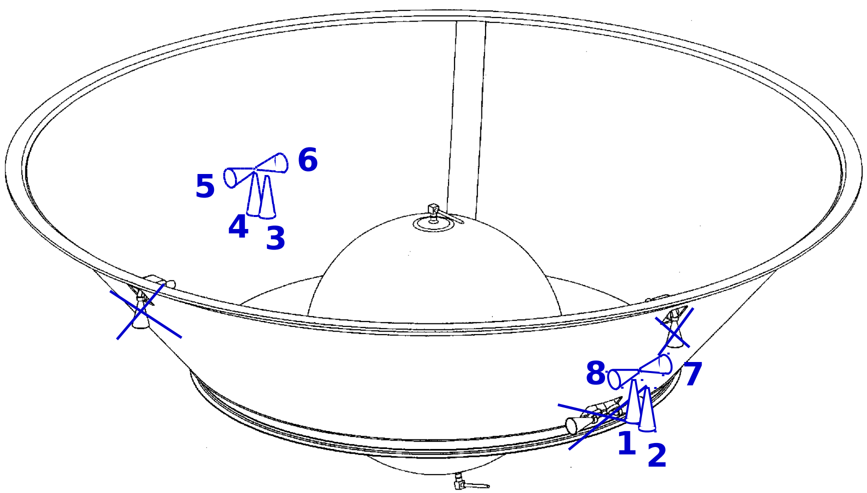
Zc.m. Wet w/AKM= 59”
Zc.m. Wet w/o AKM/interstage= 89”

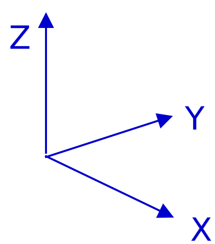
Alternate Thruster Configuration

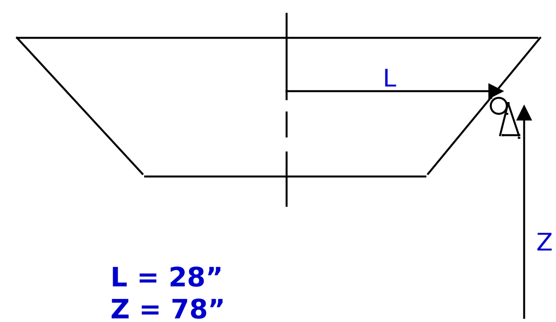
- **Under evaluation**
  - **reduces plumbing by grouping all thrusters into two pods**

Thruster sizing
1,3: 5 lbf
2,4,5-8: 0.22 lbf

	Thrust unit vecto		
ID	**x**	**y**	**z**
1	**0**	**0**	**1**
2	**0**	**0**	**1**
3	**0**	**0**	**1**
4	**0**	**0**	**1**
5	**0**	**1**	**0**
6	**0**	**-1**	**0**
7	**0**	**-1**	**0**
8	**0**	**1**	**0**







L = 28”
Z = 78”

Zc.m. Wet w/AKM= 59”
Zc.m. Wet w/o AKM/interstage= 89”

Thruster Usage

THRUSTER SELECTION		
Function	Mode	Thruster Set
Spin-up/down	CLS	5-8
Active Nutation Control	ANC	1 or 3
Spin Axis Precession	SAP	1 or 3
ΔV Using ACS Jets	IP	1 & 3, Off-pulsed for X ctrl; 2,4,5-8 for Y and Z ctrl*
3-Axis Deadband Control & Slew Maneuvers	IP	2,4, 5-8

IP=Inertial Pointing
CLS=Closed Loop Spin

* for Alternate thruster config: 1 & 3, Off-pulsed for Y ctrl; 5-8 for X and Z ctrl

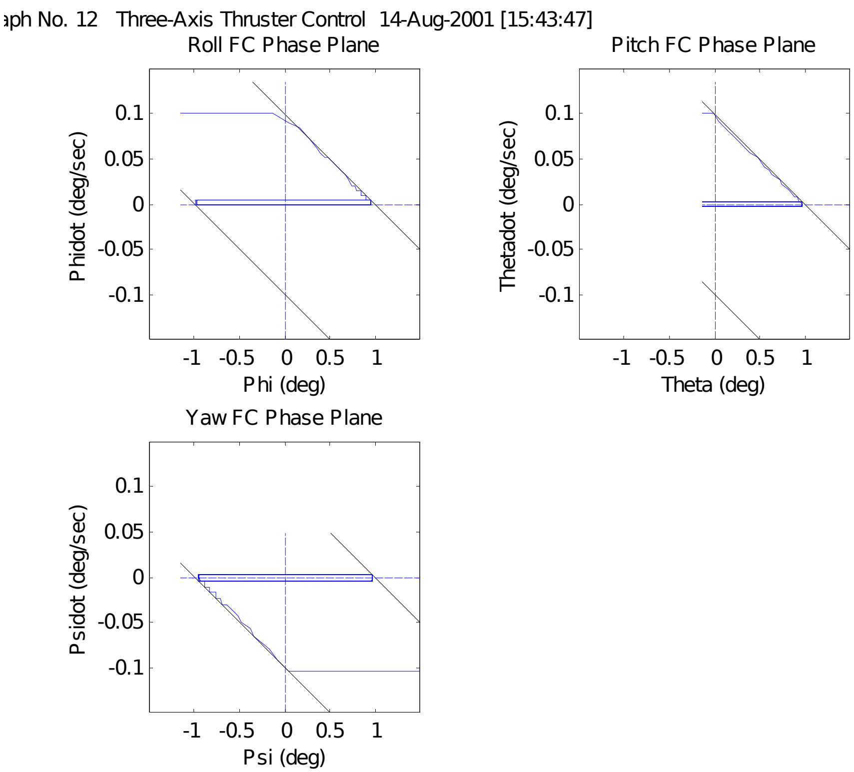
ACS Prop Budget

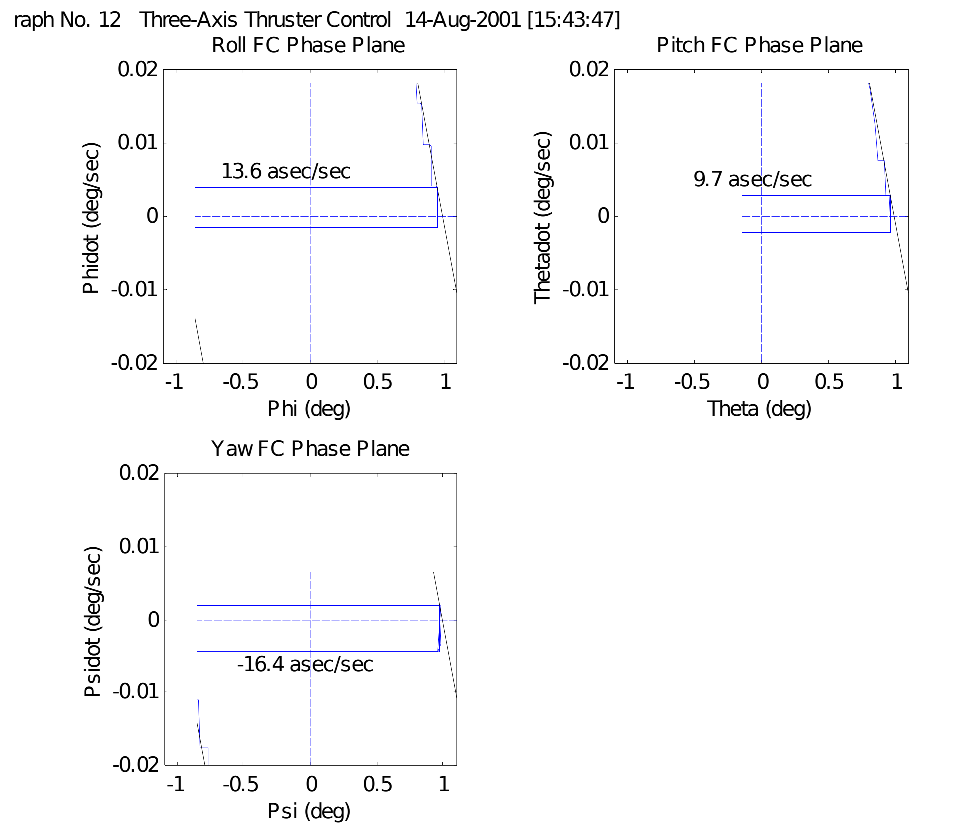
	Configuration	Mprop (kg)	Mprop (lbm)
1	Flight Vehicle, Stowed, Wet AKM	11.2	24.7
2	Flight Vehicle, Stowed, Dry AKM	6.1	13.4
3	Spacecraft, Stowed, Wet	0.1	0.3
4	Spacecraft, Deployed, Wet	2.7	6.1
	total	20.2	44.5

1	Flight Vehicle, Stowed, Wet AKM		
	Null tip-off from Delta 3rd stage	0.17	
	Inertial pointing (3-axis limit cycle)	0.05	
	Slew maneuvers	0.22	
	SHM spin-up/down	0.07	
	AKM spin-up	1.55	
	Active Nutation Control	8.80	
	Spin axis precession	0.35	
	subtotal	11.2	kg
2	Flight Vehicle, Stowed, Dry AKM		
	ANC following AKM firing	1.73	
	Post-AKM spin-down	1.25	
	Slew maneuvers	2.48	
	Inertial ptg during ACS Delta-V	0.21	
	Inertial pointing (3-axis limit cycle)	0.43	
	subtotal	6.1	kg
3	Spacecraft, Stowed, Wet		
	Slew maneuver	0.03	
	Inertial pointing (3-axis limit cycle)	0.10	
	subtotal	0.1	kg
4	Spacecraft, Deployed, Wet		
	Slew maneuvers	0.30	
	Inertial pointing (3-axis limit cycle)	1.36	
	Inertial ptg during ACS Delta-V	0.32	
	SHM spin-up/down	0.77	
	subtotal	2.7	kg

Thruster Control Simulation: 3-Axis Deadband Control

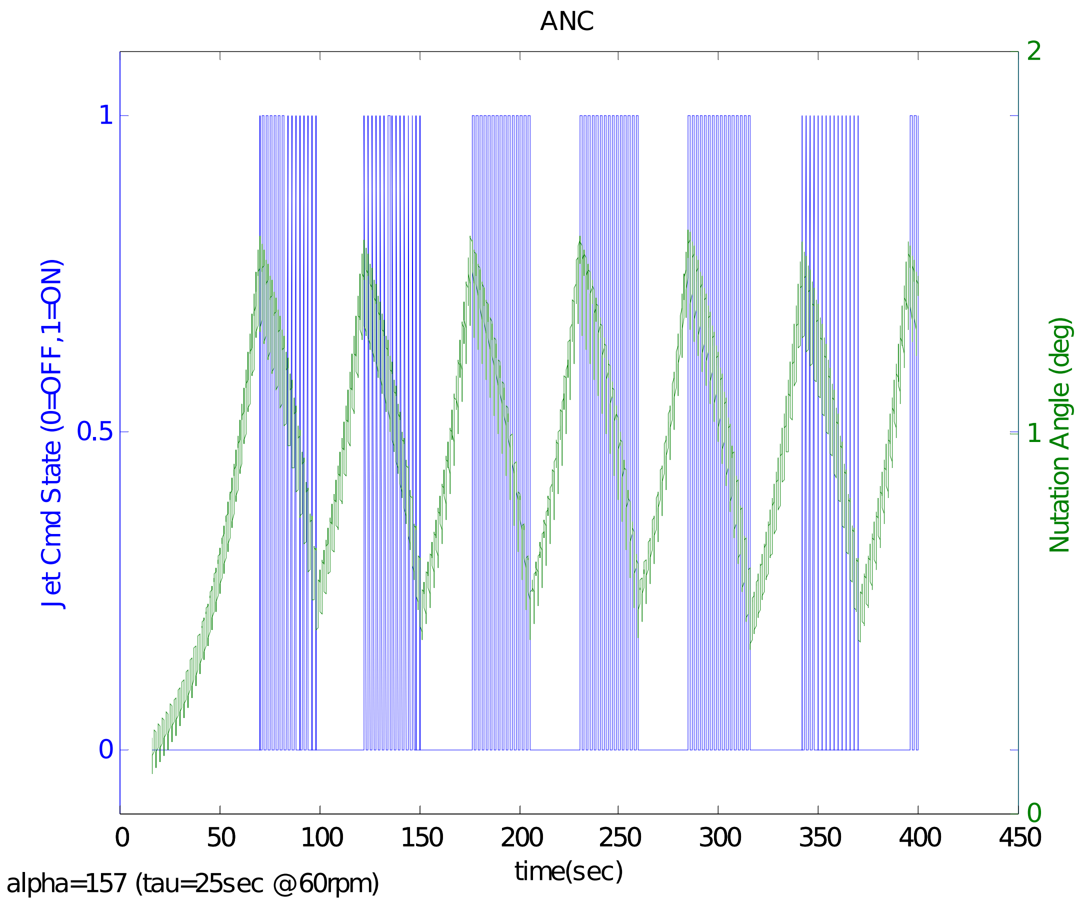
- **Three-axis control using six 0.22 lbf thrusters (2, 4-8)**
  - **Initial small angle offset per axis, ICM switch curve controller**





Thruster Control Simulation: Active Nutation Control

- **Single 5-lbf Thruster**
  - **Wet w/AKM mass prop's, 1.5deg turn-on threshold, 0.5 deg turn-off threshold, τ = 25 sec.**

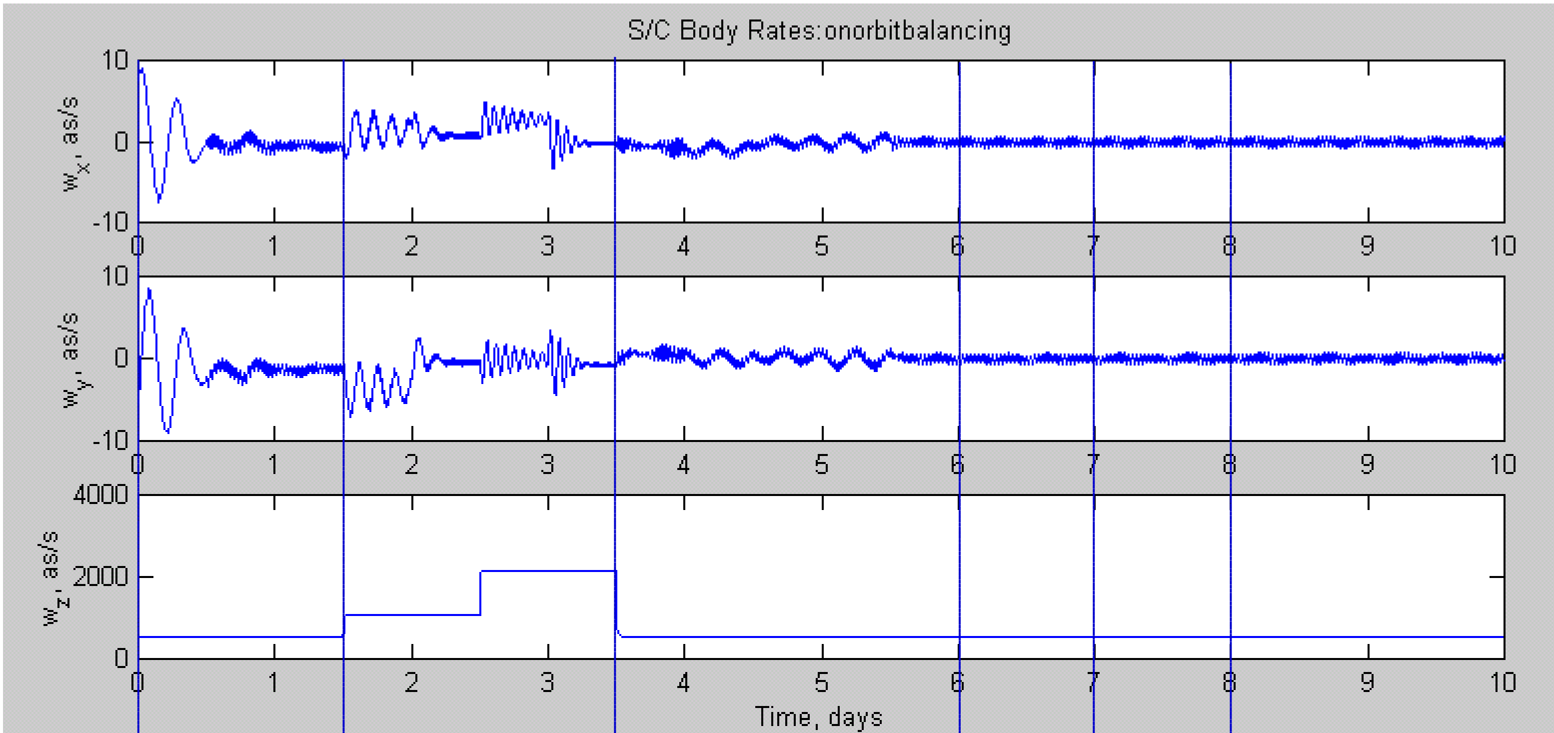


ADCS Cost and Design Options

Technical Interchange Meeting
August 15-16, 2001
Naval Research Laboratory

On-Orbit Balancing

- **Sequence of events (FAME "Classic")**



- Precession rate control (trim tabs)
- Dynamic balancing (trim masses)
- Static balancing (trim areas)
- Spin rate control (heaters)

All actuators turned off

Performance Summary

- **Performance achieved after each balancing phase (FAME "Classic")**

Performance indicators / Actuator status	Requirement	Precession rate balancing (trim tabs)	Dynamic balancing (spin axis misalignment, trim masses)	Static balancing (CM-CP offset, trim areas)	Spin rate balancing (heater patches)	Final balanced status (no active control)
Mean TDI update interval, min	N/A	14.9	13.8	16.9	56.8	25.0
Minimum TDI update interval, min	>5 (TBR)	4	4	6	9	5
Mean cross scan motion, pixels	[abs(mean) + 1-sigma] < 6.5 pixels (TBR)	-5.4	-0.2	-0.1	-0.2	-0.1
1-sigma cross scan motion, pixels		10	4.7	2.9	2.9	3.0
EMT		ON	OFF	ON	OFF	OFF
Trim tabs		ON	OFF	OFF	OFF	OFF
Trim masses		OFF	ON	OFF	OFF	OFF
Trim areas		OFF	OFF	ON	OFF	OFF
Heater patches		OFF	OFF	OFF	ON	OFF
Remarks		- Spin rate control - Initial nutation damping	- Spin up to 20 and 10 min periods during balancing		- Has been removed	

ADCS Hardware Cost and Descope Options

- **Cost Estimates (in $1,000)**

ADCS Hardware	Revised Baseline	Revised Baseline with Single Sting	ICM HW Reuse	ICM HW Reuse with Single String on New Items	ICM HW Reuse with Acquisition Performance Degradation	ICM HW Reuse with Acquisition Performance Degradation & Single String on New Items
IMU	$ 302	$ 151	$ 0	$ 0	$ 0	$ 0
ST	$ 1,074	$ 537	$ 1,074	$ 537	$ 0	$ 0
SSS	$ 200	$ 100	$ 200	$ 100	$ 0	$ 0
EMT	$ 130	$ 86	$ 130	$ 86	$ 130	$ 86
TAM	$ 124	$ 62	$ 62	$ 62	$ 62	$ 0
Total	$ 1,830	$ 936	$ 1,465	$ 785	$ 192	$ 86
Remarks	- All new items - IMU (2) - ST(2) - SSS (2) - EMT (3) - TAM (2)	- No redundancy for any hardware - IMU (1) - ST(1) - SSS (1) - EMT (2) - TAM (1)	- ICM IMU (2) - New ST(2) - New SSS (2) - New EMT (3) - New TAM (1), ICM TAM (1)	- ICM IMU (2) - New ST(1) - New SSS (1) - New EMT (2) - New TAM (1), ICM TAM (1)	- ICM IMU (2) - ICM ST (2) with Degraded Performance - ICM 5-EYE DSS for SSS - New EMT (3) - New TAM (1), ICM TAM (1)	- ICM IMU (2) - ICM ST (2) with Degraded Performance - ICM 5-EYE DSS for SSS - New EMT (2) - ICM TAM (1)

- **ICM hardware availability has not been determined.**

ST Capability vs. Science Acquisition Requirements

	FAME ST Requirements	ICM ST Requirements	ICM COCA ST Error Budget
Roll and pitch axes	+/- 50 μrad	+/- 500 μrad	+/- 400 μrad
Yaw (boresight) axis	+/- 150 μrad	+/- 1,500 μrad	+/- 1,200 μrad
Science acquisition window requirement	600 x 600 pixels (+/- 390 μrad)		

- Current science acquisition window is too small for ICM COCA ST to meet.
- ICM ST will be feasible for FAME only if the science acquisition window is opened up to cover the entire half CCD (1k x 2k pixels, 1,300 μrad x 2,600 μrad)
- Other issues for ICM ST integration
  - Examine ICM specific ST operation constraints/requirements to improve error budget (e.g., 0.5 deg/sec slew maneuver)
  - Examine impact on CT&DH and FSW.
  - Use two ST's simultaneously to improve attitude measurement accuracy

FAME Control Trade

	FAME Baseline – Solar Precession	Active Control – EP Thrusters	Active Control – Reaction Wheels
Control Approach	Passive/Active	Active On-Off Control	Active Proportional Control
Meets Science Derived ADCS Requirements	Yes	Yes (TBR)	Yes (TBR)
ADCS H/W Actuators needed	EMTs, Trim Tabs, Trim Masses, Trim Area	EP Thrusters (e.g., PPT)	Reaction Wheels
ADCS H/W Sensors needed	STs, IMUs, TAMs, SSs, Instrument	STs, IMUs, SSs, Instrument	STs, IMUs, SSs, Instrument
Mass Property Requirement (Inertia, CM)	Stable Spinner, Stringent Tolerances	Stable Spinner, Less Stringent Tolerances	Relaxed Tolerances
CM-CP Offset Requirement	Stringent	Less Stringent	Relaxed
Optical Property Requirements	Stringent	Less Stringent	Relaxed
Deployment/Geometry Requirements	Stringent	Less Stringent	Relaxed
Residual Magnetic Dipole Requirement	Stringent	Less Stringent	Relaxed
Potential Cost Savings	N/A	• Elimination of EMTs, TAMs • Elimination of trim tabs, trim areas, trim masses • Greater flexibility in thermal control design • Simplification of ground spin balancing • Simplification of ground magnetic balancing	
Cost Growth for Active	N/A	• Cost of EP	• Cost of reaction

Alternative FAME ACS Design Using Reaction Wheels

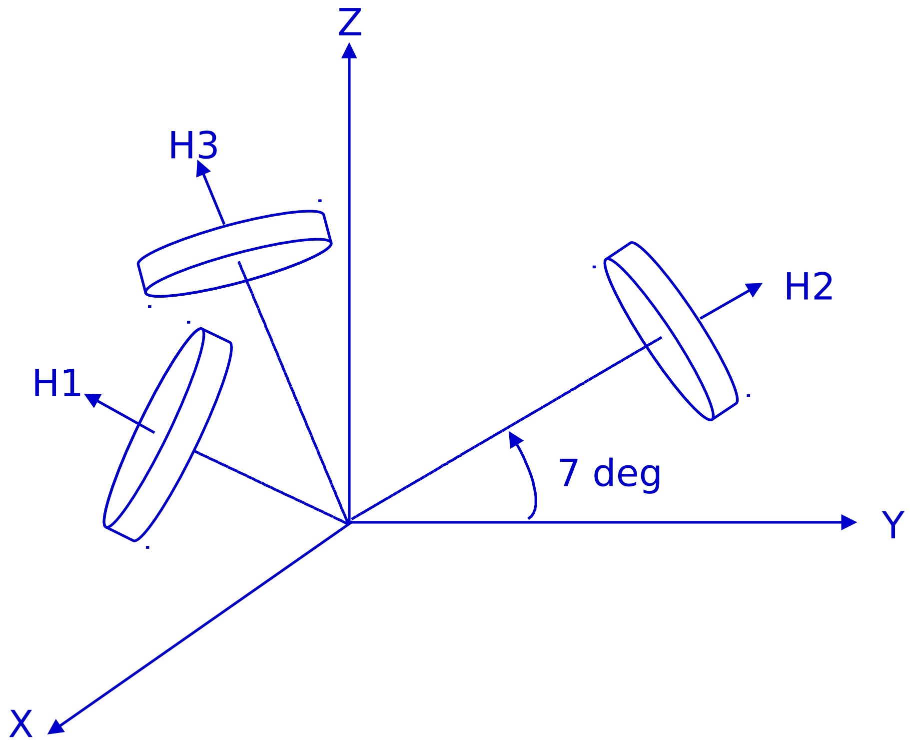
Technical Interchange Meeting

August 15-16, 2001

NRL

Reaction Wheel Placement

- **Three RW separated by 120 deg in the X-Y plane and elevated by 7 deg toward the spin (Z) axis**

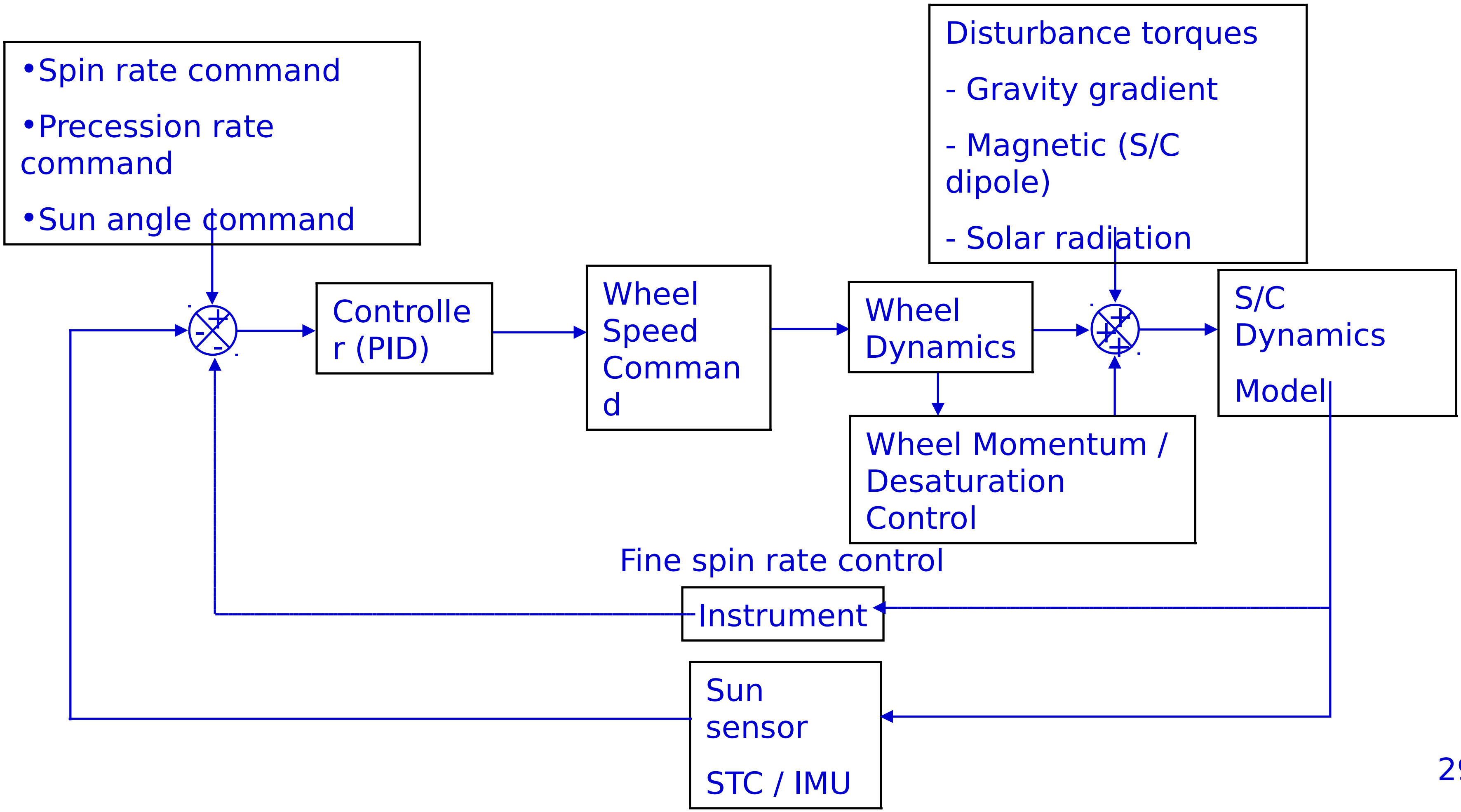


Candidate RW Specification

Unit specification	HR0610 (Honeywell)	TW-4A12 (Ithaco)	Remarks
Momentum capacity (N-m-s)	4 to 12	4	
Max. torque (mN-m)	75	12	
Speed (rpm)	+/- 6000	+/- 5100	
Peak power (W)	80	25	
Steady state power (W)	15	9	At max. speed
Static imbalance (g-cm)	<1.5	<0.5	
Dynamic imbalance (g-cm^2)	<40	<10	
Mass (kg)	3.6 to 5.0	3.46	Motor driver included
Dimension (Diameter x height, cm)	26.7 x 12 (Wheel and motor drive)	20.5 x 6.4 (Wheel) 15 x 19 x 32 (Motor drive)	

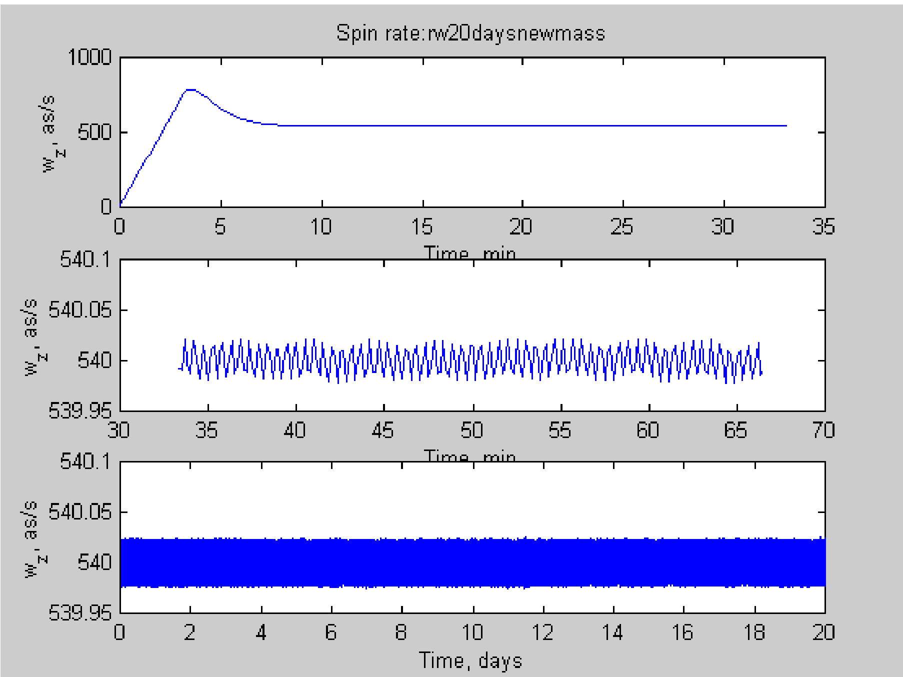
RW Control Block Diagram

- Near zero bias momentum system: spin up to 40 +/- 4 min spin period using RW system.
- Precession rate, sun angle, and coarse spin rate control using STC/IMU and sun sensor.
- Fine spin rate control using instrument spin rate measurement data.

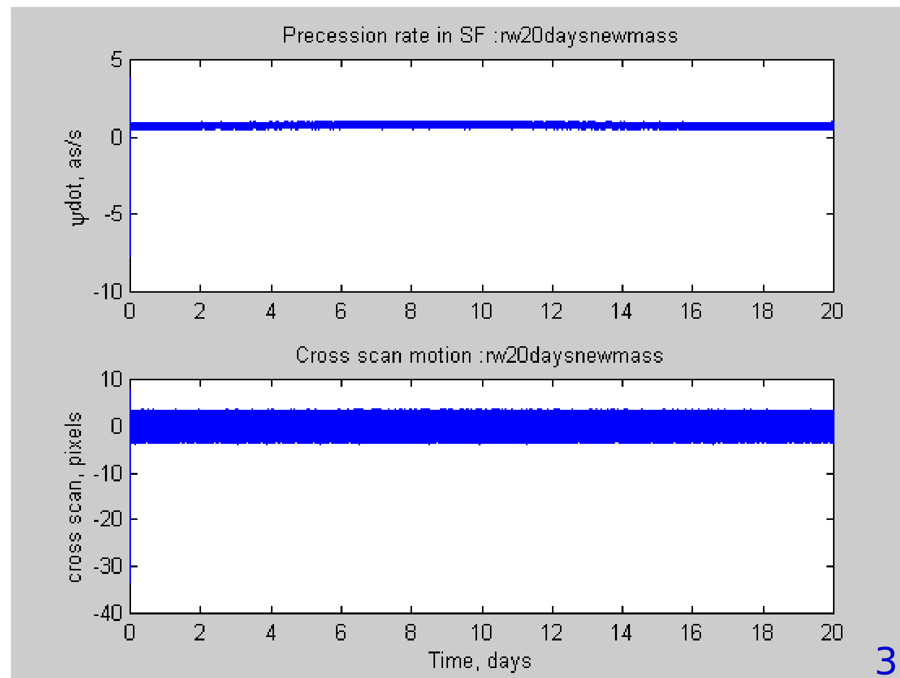


RW Control Performance (1/3)

- **Representative errors included: environmental torque (gravity gradient, magnetic, solar radiation), RW torque noise**
- **Ithaco RW (TW-4A12) specification employed**



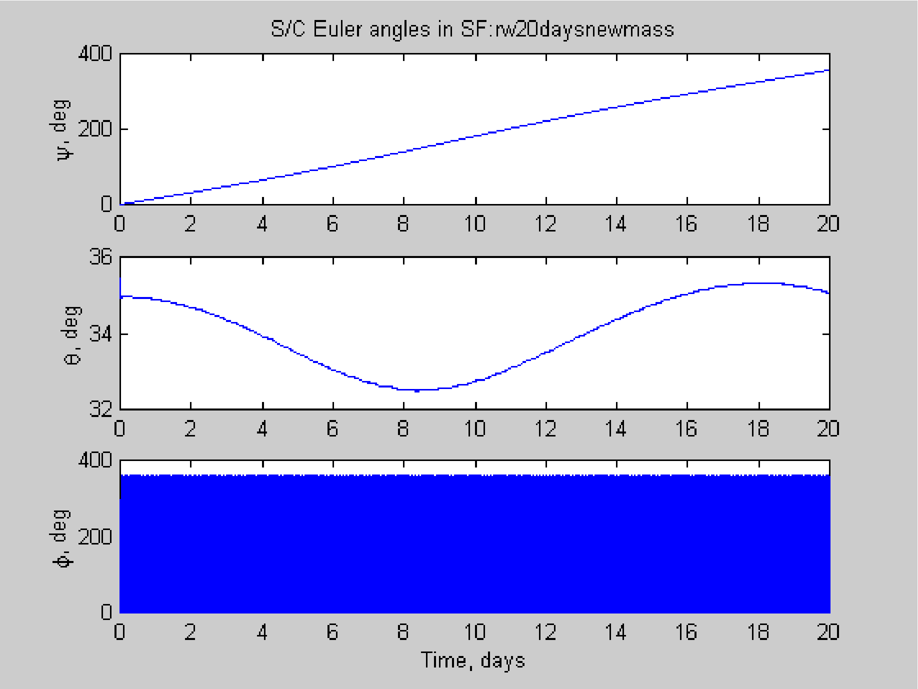
- **Spin rate control**
  - **Initial spin up to the 40 min period takes less than 10 min**
  - **Variation well within +/- 0.05 as/s boundary**



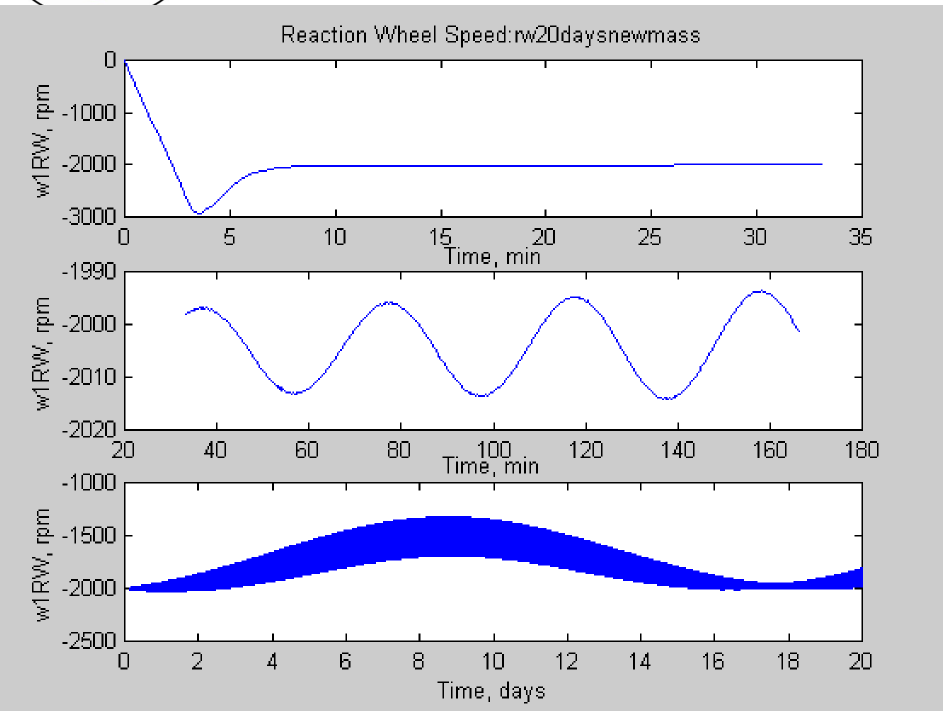
- **Precession rate control**
  - **Cross-scan stays well within +/- 10 pixel boundary**

RW Control Performance (2/3)

- **Sun angle control**
  - **Well within 35 +/- 5 deg boundary**

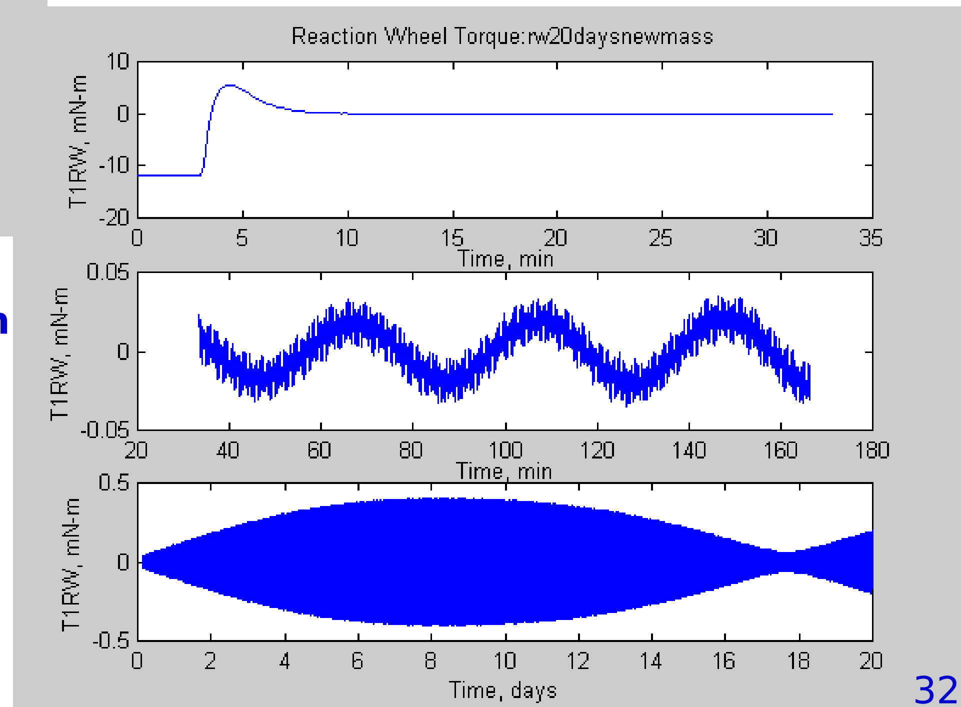


RW Control Performance (3/3)



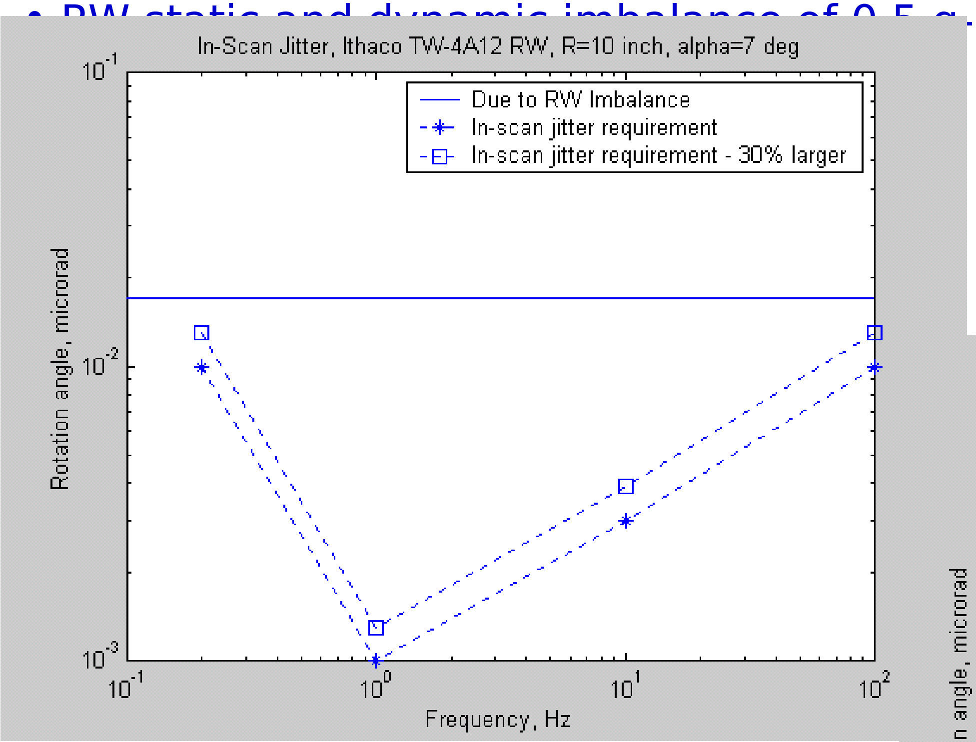
- **Wheel speed**
  - **2,000 rpm to spin up S/C at 40 min spin period**
  - **Speed range stays between 1,300 rpm and 2,100 rpm during a precession period**
  - **Speed cycles at the spin period with an amplitude range of 10 rpm to 200 rpm**

- **Wheel torque**
  - **Initial torque saturation at 12 mN-m to spin up the S/C**
  - **Torque cycles at the spin period with an amplitude range of 0.02 mN-m to 0.4 mN-m.**
  - **RW produces torque noise of amplitude of 0.015 mN-m at 30 sec period**

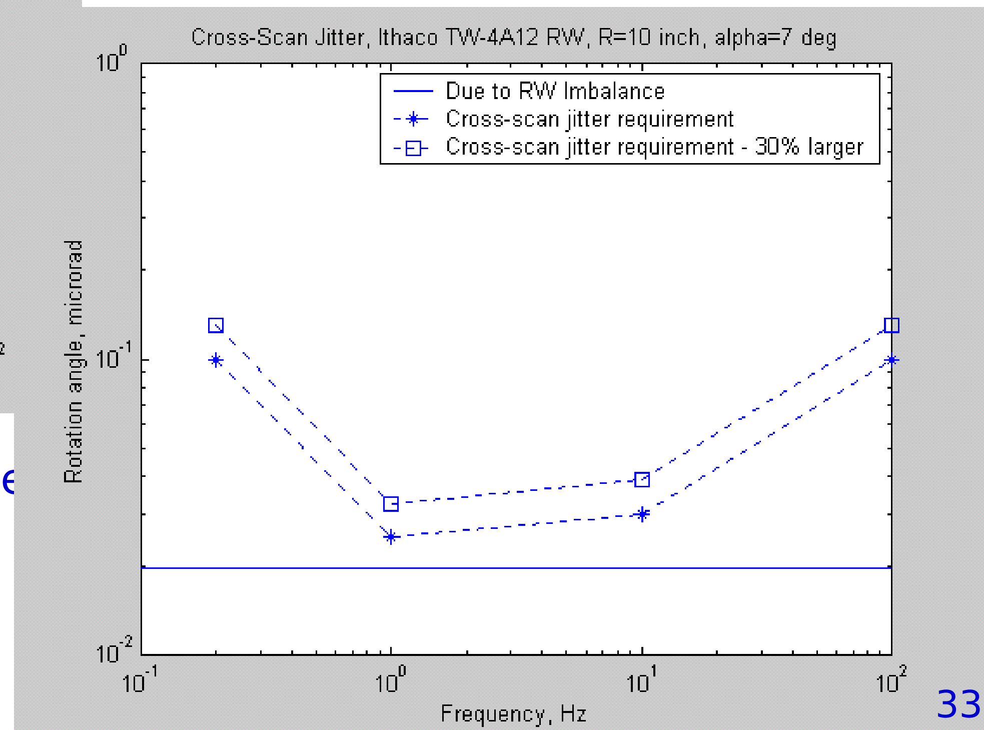


Jitter Produced By RW Imbalance

- Three RW's located at 10 inches from the spin axis elevated 7 deg from the transverse plane.
- RW static and dynamic imbalance of 0.5 g-cm and 10 g-cm^2, respectively (Ithaco



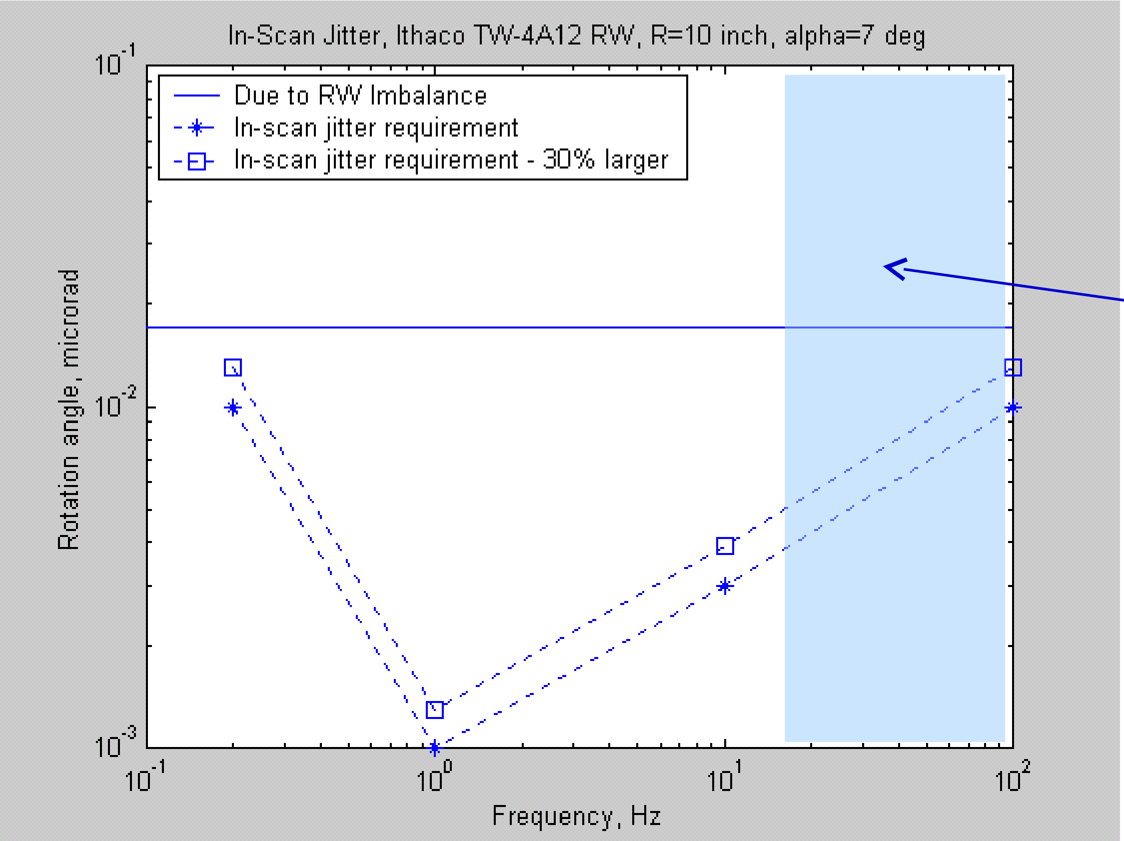
- In-scan jitter requirements are violated.
- 30% increase in pixel size help alleviate jitter requirements



- Cross-scan jitter requirements are me

RW Operation Strategy for Jitter Mitigation

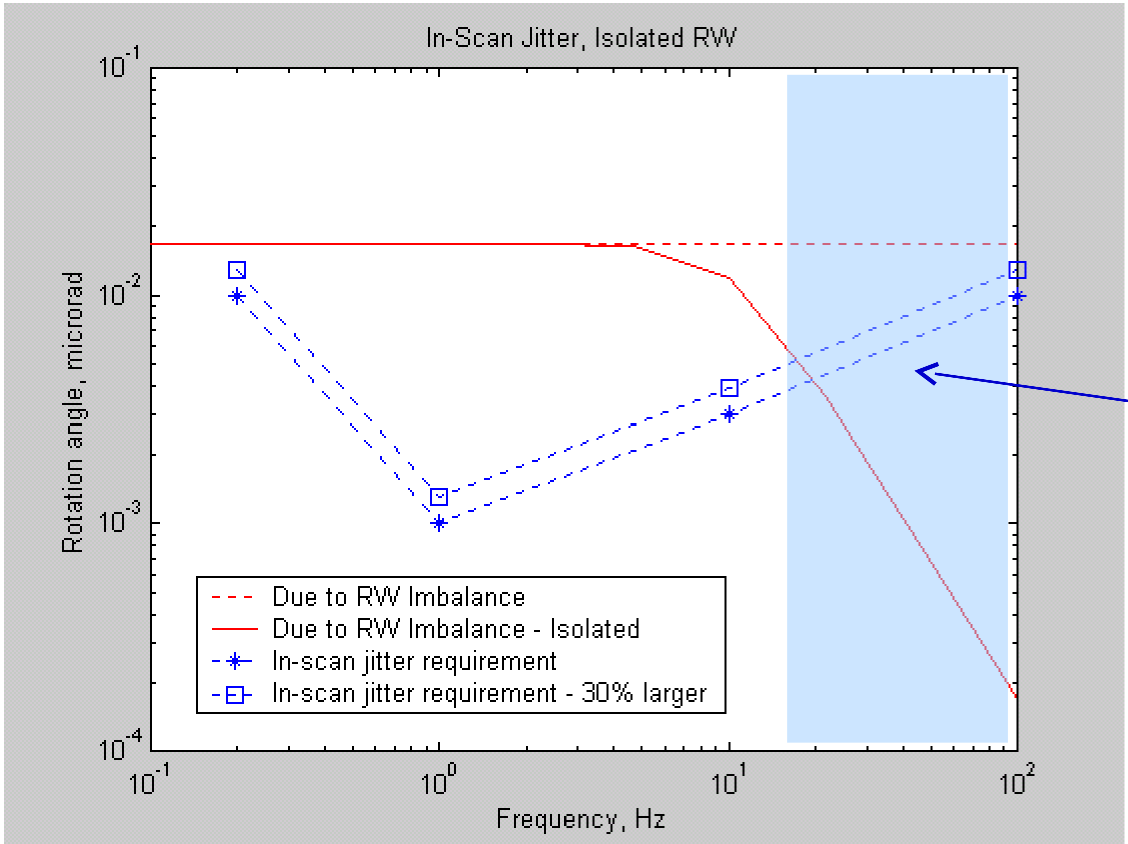
- **Limit the RW speed above 1000 rpm (16.7 Hz) to avoid stringent frequency range of 1-10 Hz.**
- **Elevation angle of RW spin axis is set at 7 deg from the transverse plane.**



RW operating speed range: > 1,000 rpm

Jitter Mitigation Using RW Isolators

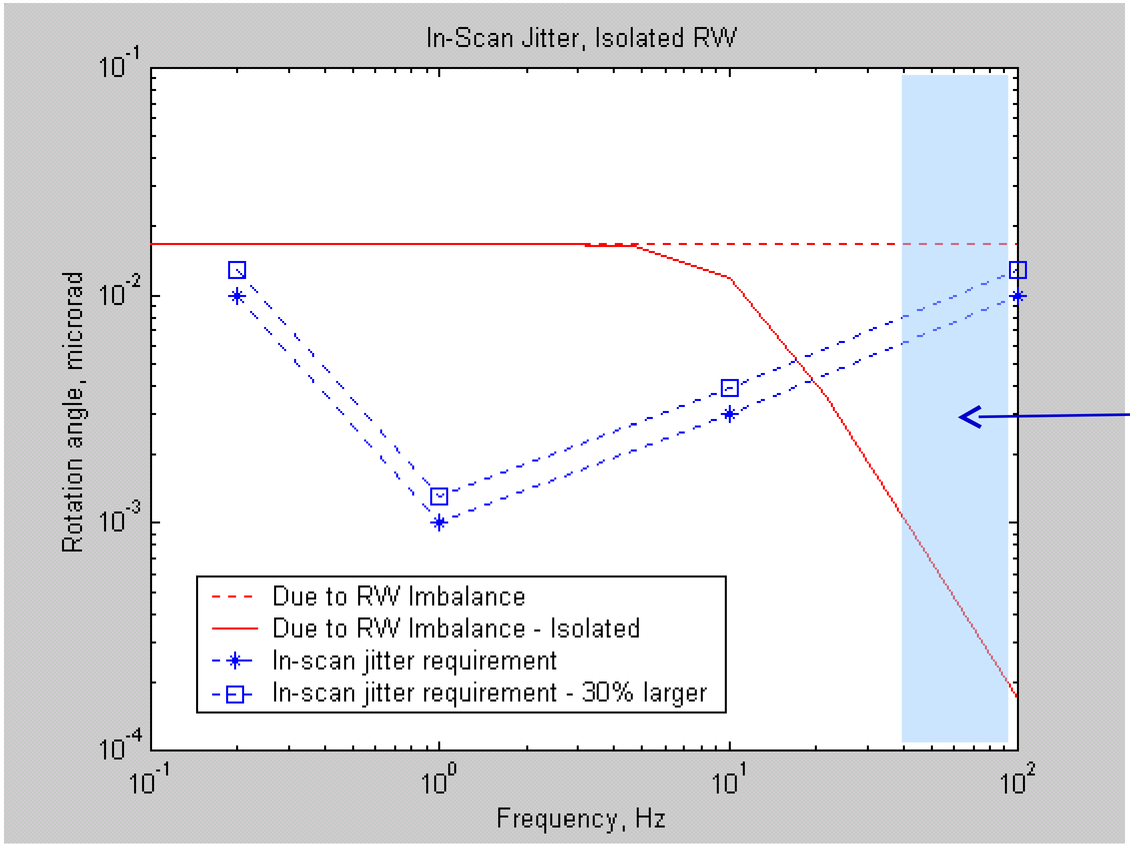
- **Honeywell MATRA Isolation System for RW attenuates vibration by 0.01 at 100 Hz.**
- **Capable of meeting the in-scan jitter requirement above the minimum RW operating speed**
- **Higher frequency disturbance due to torque ripple (which is 108 times of the wheel speed for Ithaco RW) will also be well attenuated.**



RW operating speed range: > 1,000 rpm

Impact of Structural Vibration on Jitter

- **Structural fundamental natural frequency is expected to be above 40 Hz thanks to the new geometry (7 Hz solar panel natural frequency for the previous design). No structural modes exist between 1-10 Hz range.**
- **Enhancing structural damping will help mitigate jitter.**
- **RW isolator will also help mitigate structure borne jitter.**



Structural modes: > 40 Hz

Alternative FAME ACS Design Using Pulsed Plasma Thrusters (PPT)

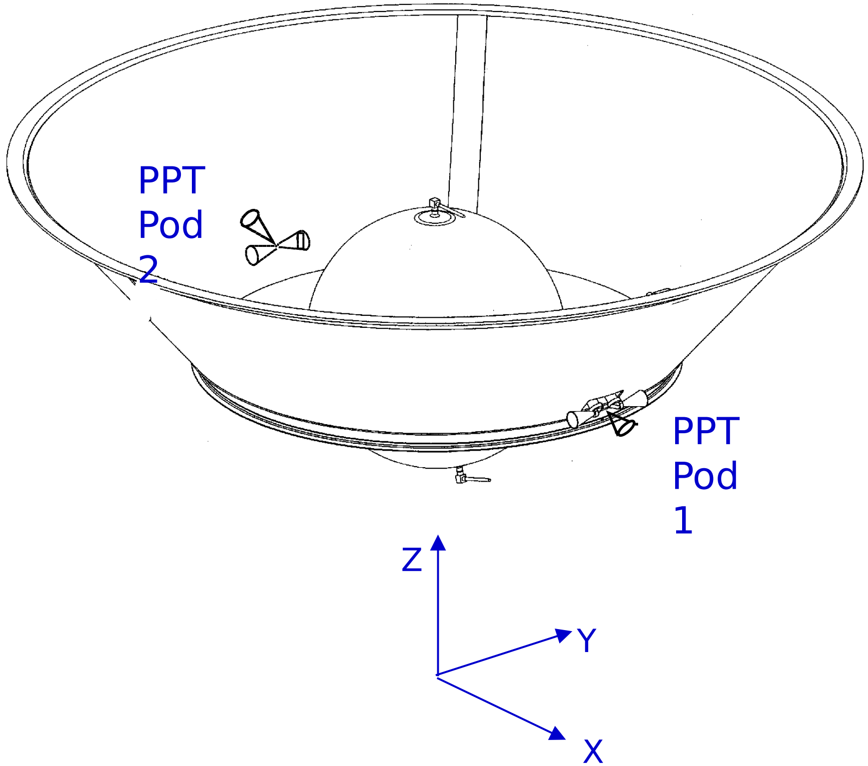
Technical Interchange Meeting

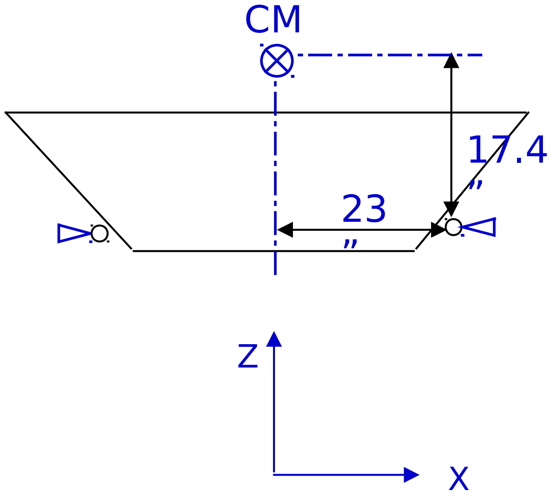
August 15-16, 2001

NRL

PPT Layout

- **Two PPT pods located along the Y-axis**
- **Each pod with 3 nozzles**
- **Three axis control capability**





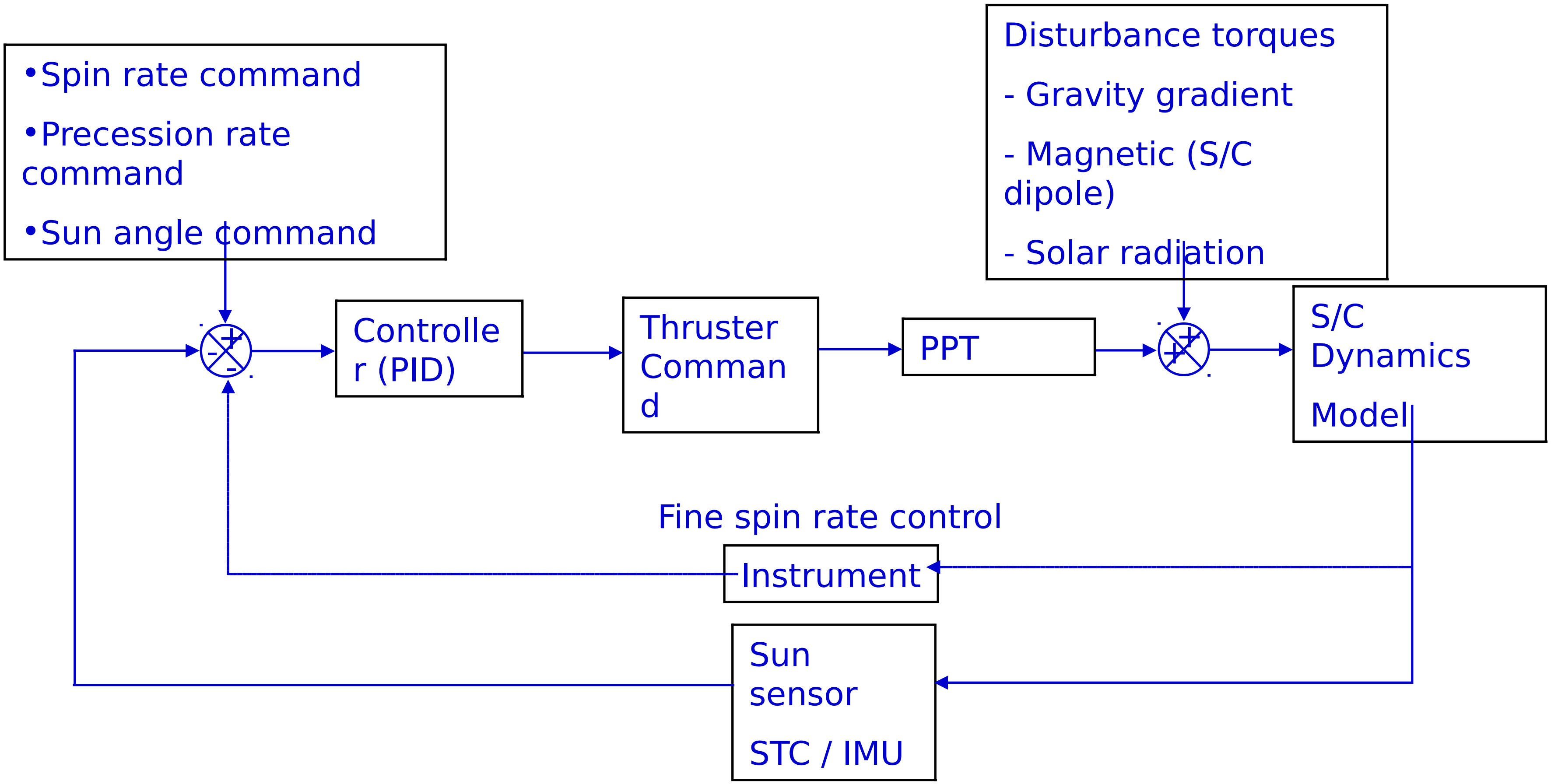
Candidate PPT Specification

- **Based on a PPT unit flown on EO-1 with two nozzles**

Unit specification	EO-1 PPT	Remarks
Impulse bit (microN-s)	90 to 860	Depends on charging time
Specific impulse (sec)	650 to 1400	
Total impulse (N-sec)	460	
Input power (W)	12 to 70	
Thruster mass (kg)	4.95	
Fuel mass (kg)	0.07	Per nozzle, fluorocarbon polymer bars

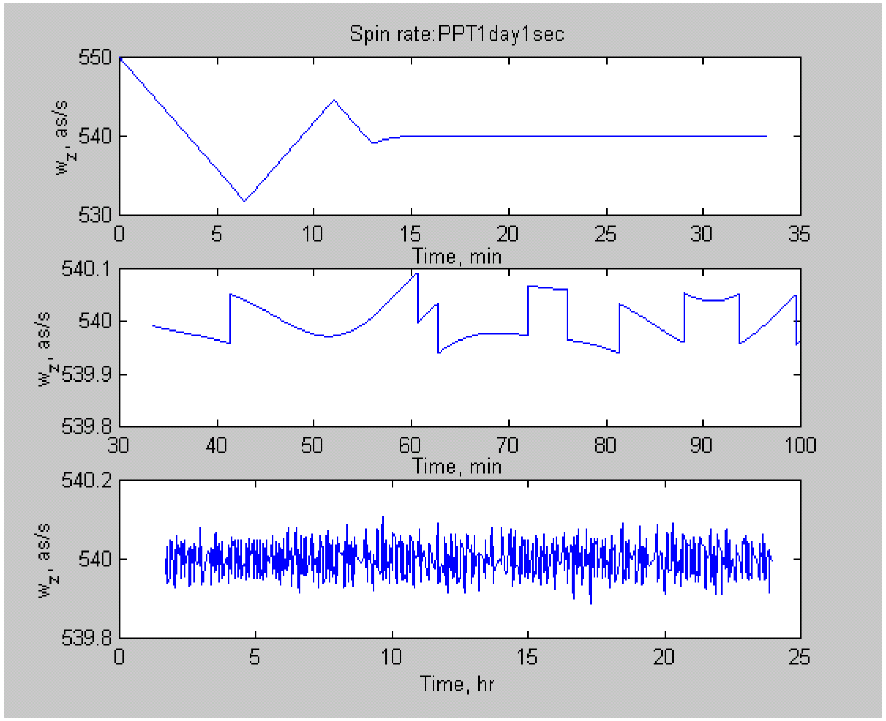
PPT Control Block Diagram

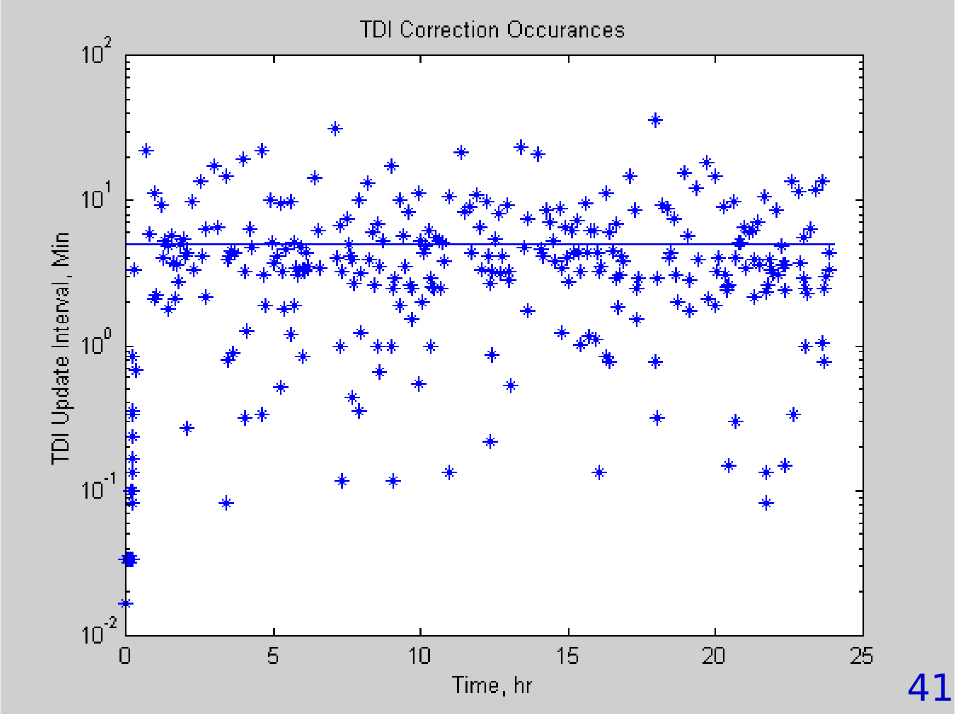
- Spin, sun angle, and precession control using PPT system.
- Precession rate, sun angle, and coarse spin rate control using STC/IMU and sun sensor.
- Fine spin rate control using instrument spin rate measurement data.



PPT Control Performance (1/3)

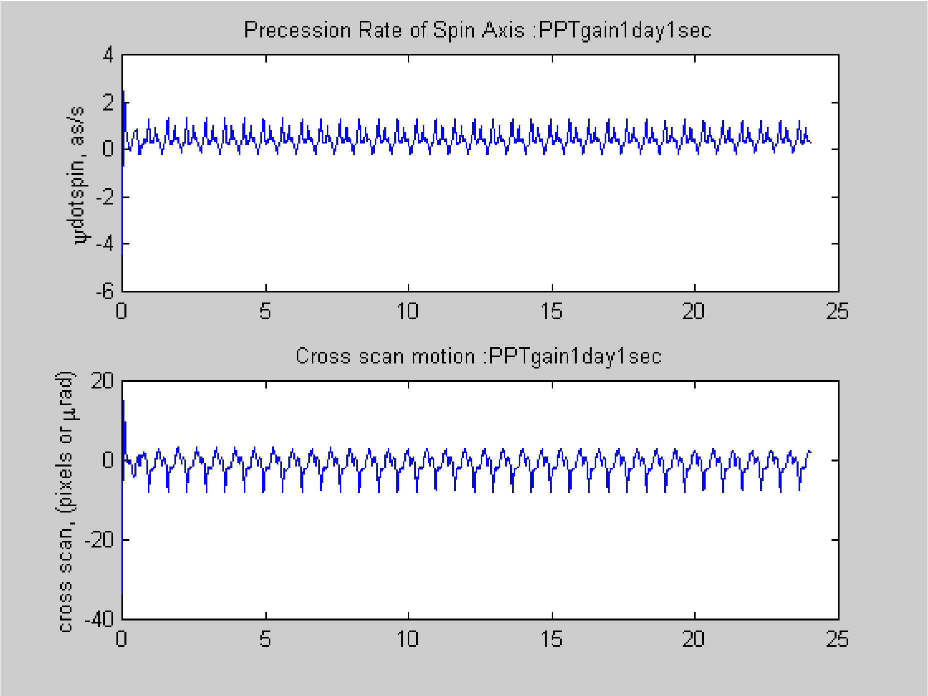
- **Representative errors included: environmental torque (gravity gradient, magnetic, solar radiation), spin axis misalignment, and CM offset**
- **90 microN PPT thruster pulsed at 1 Hz**
- **Spin rate control**
  - **Initial spin rate error control**
  - **Hold rate at 540 as/s**
  - **Variation after initial transients: 0.035 as/s (1-sigma)**
- **TDI update rate**
  - **Mean: 5.02 min**
  - **Variation: 4.96 min (1-sigma)**

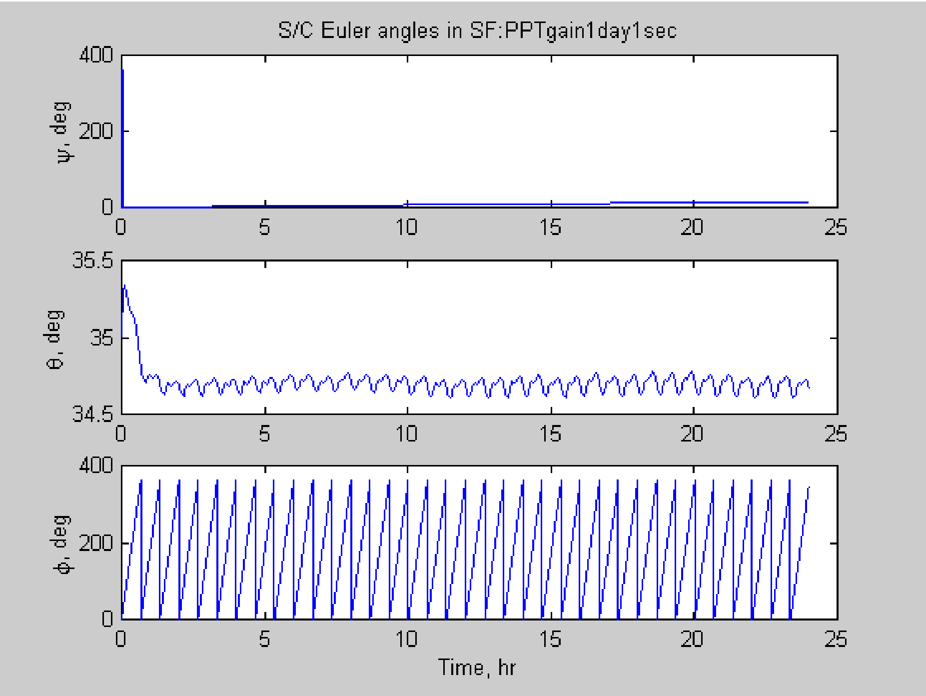




PPT Control Performance (2/3)

- **Precession rate (cross-scan) control**
  - **Mean cross-scan: -0.9 pixel**
  - **Variation: 2.4 pixel (1-sigma)**
- **Sun angle control**
  - **Well within 35 +/- 5 deg boundary**





PPT Control Performance (3/3)

- **PPT firing statistics**
  - **Total impulse (N-s) per day: 0.078 (X), 0.135 (Y), 0.063 (Z)**
  - **Total impulse (N-s) needed for a 5 year mission: 142.4 (X), 247.0 (Y), 114.6 (Z), well within the 460 N-s capability**
  - **Number of pulses per day: 981 (X), 3,402 (Y), 597 (Z)**
  - **Number of pulses needed for a 5 year mission: 1.79M (X), 6.21M (Y), 1.09 (Z), well within the reported pulse capability of 40M**